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GATC Final Report MRD 1240-1

ANALYSIS OF ABOVEGROUND FALLOUT SHELTER VENTILATION REQUIREMENTS

Prepared by

General American Transportation Corporation

MRD DIVISION

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Prepared for
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MRD DIVISION

GENERAL AMERICAN TRANSPORTATION CORPORATION

FOREWORD

This report was prepared by the MRD Division of the General American Transportation Corporation under Contract OCD-OS-63-176 for the Office of Civil Defense. Mr. Frank C. Allen of OCD's Directorate of Research was project monitor. This report covers the period of June 1963 to August 1964. The contract was a study of the habitability of typical identified shelter configurations with consideration given to various space allotments, ventilating rates, environmental criteria, and structural particulars. All of these parameters were studied over a wide range of variation with the primary emphasis on aboveground shelter spaces.

Analytical studies of the environment in shelters are continuing under a subcontract with Stanford Research Institute, and a comprehensive report will be prepared at the conclusion of planned work.

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ABSTRACT

Transient and steady analysis are used to determine the psychrometric conditions that develop in large aboveground fallout shelters ventilated with unconditioned ambient air. These analyses consider the shelter size, geometry and construction, the psychrometric condition of the ambient weather, and the various metabolic and nonmetabolic heat loads to the shelter air. The results of this study indicate that during the hot summer weather, only a small fraction of the total energy input to the shelter is lost through the shelter boundary surfaces. Thus, the ventilation requirements for large aboveground shelters can be obtained by the use of an analysis which neglects the heat loss through the shelter boundaries. This means that aboveground shelter ventilation systems should be designed to remove the entire thermal load generated within the shelter.

INTRODUCTION

The fallout shelter must protect the shelter occupants from radioactive fallout and from the detrimental effects of excessive carbon dioxide levels, insufficient amount of oxygen, and excessive shelter temperatures and humidities. The shelter ventilation system's equipment insures that these additional safeguards are maintained. For example, the carbon dioxide level in a shelter can be kept at an acceptable value by ventilating the shelter with 3 cfm per occupant. But, as much as 60 cfm of outside air could be required to keep the shelter temperature and humidity down to tolerable limits during the hot summer months. In some situations, ventilating with external ambient air will not sufficiently control the shelter effective temperature and air conditioning equipment will be required.

To properly select the ventilation equipment, the shelter designer must accurately know the ventilation rate required. The major parameters in this determination are the number of shelter occupants, the shelter's geographical location, and the shelter's size and construction. The number of occupants establishes the level of latent and sensible metabolic heat that is produced in the shelter. The geographical location determined that statistical probability and frequency of occurrence of the psychrometric condition of the ambient weather from which the weather design criteria can be obtained. A knowledge of the shelter's physical size and construction features defines the heat transfer coefficients which are required to compute the heat transfer to and from the shelter. When these factors and the required shelter effective temperature are known and incorporated into a prediction technique for the ventilation requirements of the shelter, the designer has a basis upon which he can select the ventilation equipment.

The MRD Division has been engaged in the development of such a prediction technique under the Office of Civil Defense Contract OCD-OS-63-176, Subtask 1215A*. The eventual goal of this program is to formulate a simplified procedure for predicting the ventilation requirements of shelters. This paper presents the results of several studies which are preliminary steps in the development of this simplified procedure. These studies are based upon

1. the metabolic energy output of approximately 400 Btu/hr-occupant given by the sensible and latent heat expression, see Reference 1,

*Mr. F. C. Allen of OCD's Directorate of Research was project monitor.

2. the shelter habitability criteria represented by the ASHRAE effective temperature (an empiracally devised index of the various phychrometric conditions that produce similar comfort levels), see Appendix A, and
3. the derived mathematical shelter model which is applicable to large shelters that are either aboveground or belowground, do or do not have boundary surface heat losses, and are in a transient or steady-state condition of mass and energy transfer, see Appendix B and Reference 1.

The mathematical model for the shelter is the most comprehensive analytical procedure that could be developed without unduly complicating the computational procedure. When used as a transient analysis, the model permits the psychrometric state of the shelter air to be computed as a function of time. The analysis considers

1. time varying inlet air conditions,
2. time varying energy inputs to the shelter air from equipment and lights,
3. time varying solar loads which have been transmitted through windows into the shelter (i.e., time varying values of transmitted solar radiation as obtained from the ASHRAE Guide and Data Book),
4. metabolic latent and sensible energy loads based upon the instantaneous psychrometric state of the shelter, see Reference 1, and
5. shelter boundary surface heat losses (or gains) based upon a one-dimensional heat transfer analysis neglecting corner effects.

The shelter model is based upon the assumption that

1. the air within the shelter is so completely mixed that all of the shelter air is at one psychrometric condition,
2. the convective heat transfer coefficient for each external boundary surface of the shelter is not a function of temperature and has a constant value over the surface,

3. the walls and floors which are internal to the shelter volume are at the dry-bulb temperature of the shelter air,
4. the radiative energy interchanges within the shelter can be neglected,
5. the solar direct and indirect radiative input to the shelter through windows and the equipment and lighting heat loads in the shelter can be grouped together as one time dependent load factor which is termed the thermal load,
6. the ventilating air exhausted from the shelter is at the psychrometric condition of the shelter air,
7. the effects of condensation on the walls, floors, and ceilings of the shelter can be neglected,
8. the thermal-physical properties of the structural materials are not temperature dependent, and
9. the solar radiation absorption on opaque shelter bondary surfaces can be neglected.

Thus the shelter is idealized as an enclosed volume in which sensible heat, latent heat, and ventilating air are introduced and from which air is exhausted and energy is lost, see Figure 1. The governing principles for

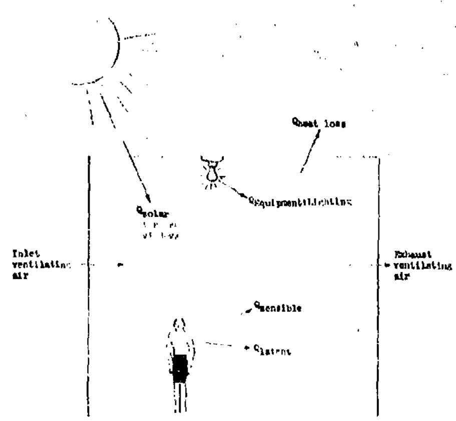


FIGURE 1 - IDEALIZED SHELTER MODEL

such a model are the conservation of energy and the conservation of the masses of dry air and water vapor.

The primary aim of this paper is to determine the most simple analytical model which can predict the psychrometric conditions which develop in aboveground shelters. To evaluate this model, actual shelter test data are compared to computed data; and variation of parameter approaches are applied to several types of shelters to generalize the results. The analytical shelter models studied in the paper are

1. aboveground adiabatic boundary shelter model (no heat transfer through the shelter boundary surfaces) with time-dependent parameters (i.e., the state of the inlet air and the thermal loads added to the shelter air),
2. aboveground nonadiabatic boundary shelter model with time-dependent parameters,
3. aboveground adiabatic boundary shelter model with steady-state (constant with time) parameters,
4. aboveground nonadiabatic boundary shelter model with steady-state parameters.

RESULTS OF SHELTER ANALYSIS

Transient Analyses of Shelters

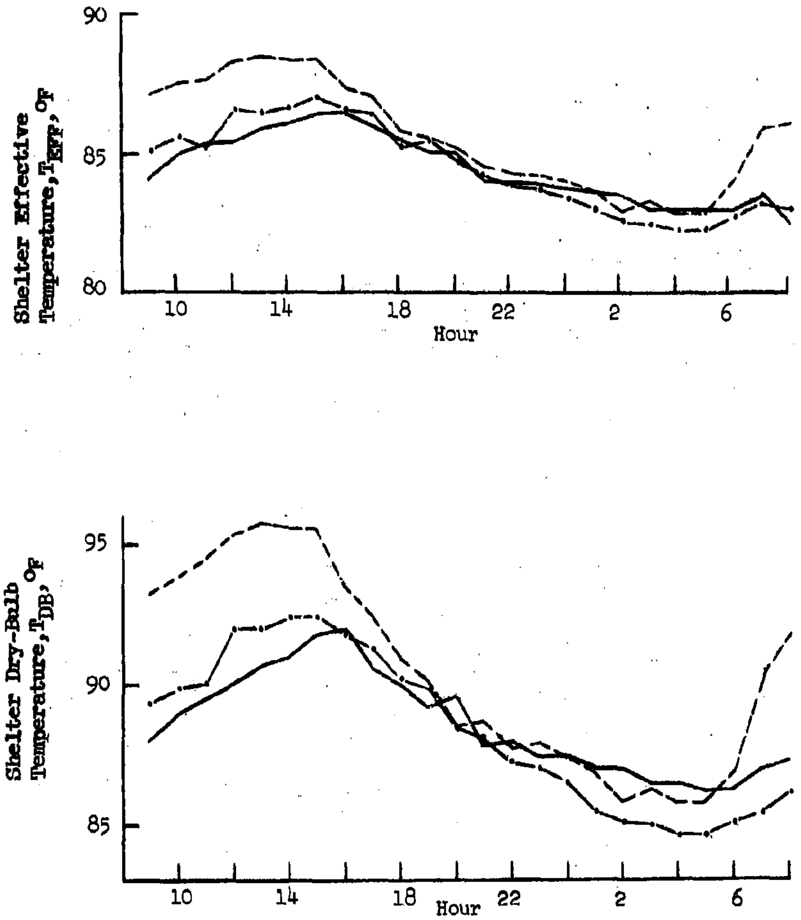
The time-history of the temperature and humidity within a shelter is predicted by the transient analysis which considers the time varying mass and energy balance about the shelter. The validity of this analysis is established by comparison of several sets of analytical computations with data from actual shelter tests. The shelter tests chosen for the comparison are the MRD Wilmington, North Carolina test #7 (Reference 2), the University of Florida

Central Stores Building test Phase IV (Reference 3), and the MRD Houston, Texas test II (Reference 4). The Wilmington shelter is a 210-man aboveground shelter, the Florida shelter is a 250-man basement shelter, and the Houston shelter is a 290-man basement shelter. Using the observed inlet air data and the shelter dimensions and construction details, the transient analysis computed the dry-bulb and effective temperatures for the shelter air as a function of time, see Figures 2, 3, and 4. The instantaneous calculated values are generally within 2°F of the experimental data for the shelter dry-bulb temperature and within 1°F for the shelter effective temperature.

When the shelter is assumed to have adiabatic boundaries (no heat transfer through the shelter boundary surfaces), the analytical and experimental results agree on the 24 hr average to within 2°F for the dry-bulb temperature and within 1°F for the effective temperature. The adiabatic boundary results are consistently at or greater than the experimental values. This means that all of the tested shelters lost energy through their boundary surfaces and that the transient analysis slightly overestimates the amount of this energy loss.

Steady-State Analysis of Shelters with Boundary Heat Loss

The time-average psychrometric condition of the shelter can be determined by the steady-state analysis which considers the time-average values of the psychrometric condition of the inlet air and the heat loads generated within the shelter. The heat loss from the boundary surfaces of an aboveground shelter is determined by the temperature difference that exists between the shelter air and the ambient air external to the shelter and by the heat loss coefficient, UA. The UA value for a shelter is determined by the size, geometry, and composition of its walls, floor, and ceiling; and its value is determined by

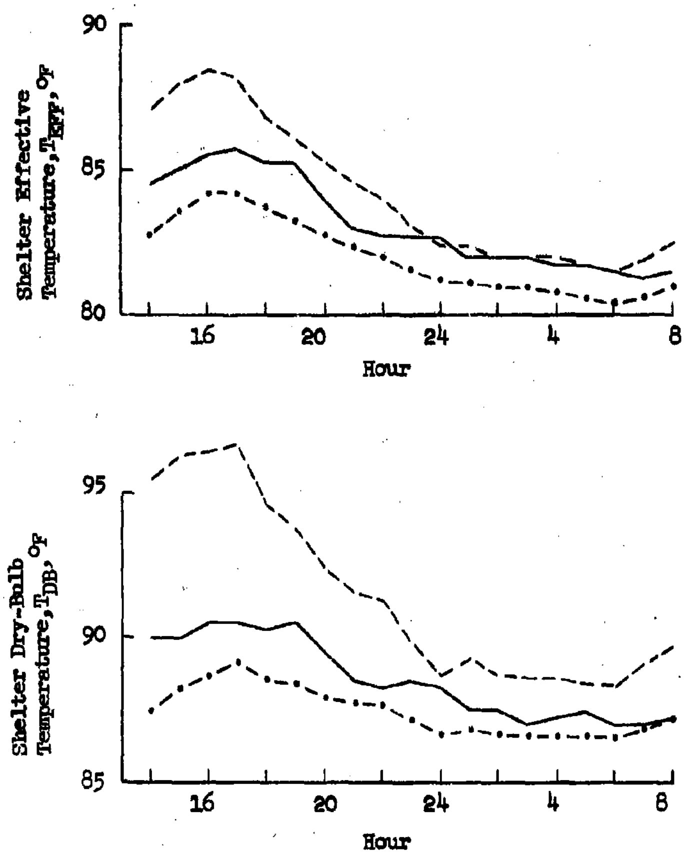


Time-Average Temperatures of Shelter Environment*

	Dry-Bulb, T_{DB}	Effective, T_{EFF}
———— : Experimental Data	88.8°F	84.5°F
– – – – : Adiabatic Boundary Computation	90.5°F	85.6°F
—·—·— : Nonadiabatic Boundary Computation	88.3°F	84.5°F

*For 20.0 CFM/OCCUPANT Ventilation Rate, 83.9°F Average Inlet Air Dry-Bulb Temperature and 80°F Average Inlet Air Effective Temperature.

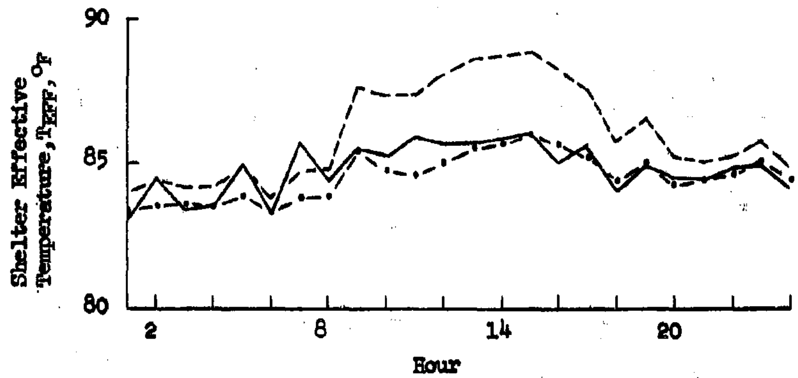
FIGURE 2 - COMPARISON OF COMPUTATIONS AND EXPERIMENTAL DATA FOR WILMINGTON, N.C. TEST 7

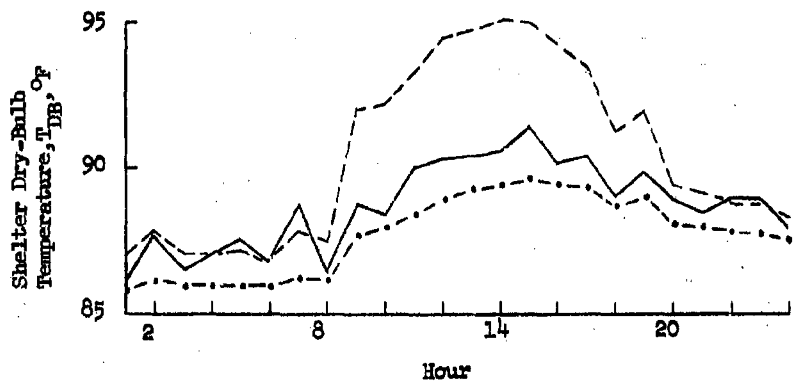


	Time-Average Temperatures of Shelter Environment*	
	Dry-Bulb, T_{DB}	Effective, T_{EFF}
———— : Experimental Data	88.6°F	83.2°F
– – – – – : Adiabatic Boundary Computations	91.5°F	84.2°F
—•—•—•— : Nonadiabatic Boundary Computations	87.5°F	82.0°F

*For 13.9 CFM/OCCUPANT Ventilation Rate, 81.5°F Average Soil Temperature, 85°F Average Inlet Air Dry-Bulb Temperature and 78.3°F Average Inlet Air Effective Temperature

FIGURE 3 - COMPARISON OF COMPUTATIONS AND EXPERIMENTAL DATA FOR CENTRAL STORES BUILDING GAINSVILLE, FLORIDA





	Time-Average Temperatures of Shelter Environment*	
	Dry-Bulb, T_{DB}	Effective, T_{EFF}
———— : Experimental Data	88.7°F	84.8°F
– – – – – : Adiabatic Boundary Computation	90.5°F	86.1°F
—·—·—·— : Nonadiabatic Boundary Computation	87.7°F	84.5°F

*For 12.8 CFM/OCCUPANT Ventilation Rate, 87.9°F Average Soil Temperature, 83.0°F Average Inlet Air Dry-Bulb Temperature and 79.0°F Average Inlet Air Effective Temperature

FIGURE 4 - COMPARISON OF COMPUTATIONS AND EXPERIMENTAL DATA FOR HOUSTON, TEXAS TEST II

$$UA = \frac{\sum_{j=1}^{m} U_j A_j}{p}$$

where:

m = number of boundary surfaces

U_j = overall heat transfer coefficient of boundary surface j*

A_j = surface area of boundary surface i

p = number of shelter occupants

To evaluate the accuracy of the analysis, the Wilmington aboveground shelter test data are compared to the results computed by the steady-state analysis with boundary heat loss. The comparison shows that the time-average shelter dry-bulb temperature is determined to about 1.5°F and the time-average shelter effective temperature is determined to about 2°F, see Table 1.

TABLE 1

SUMMARY OF WILMINGTON, N. C. ABOVEGROUND SHELTER TEST**

Observed Data	Test Nos. 5	7	8	10A
Ventilation Rate, cfm/occupant	9.0	20.0	7.0	13.0
Average Inlet Dry-bulb Temp., °F	83.1	83.9	77.5	90.4
Average Inlet Effective Temp., °F	78.6	80.7	74.4	80.1
Average Inlet Relative Humidity	0.68	0.78	0.72	0.41
Average Shelter Dry-bulb Temp., °F	90.0	88.8	89.8	94.9
Average Shelter Effective Temp., °F	85.7	84.5	86.1	85.4
Values Predicted by Steady-State Analysis with Boundary Heat Loss				
Shelter Dry-bulb Temp., °F	90.3	90.2	87.3	95.6
Shelter Effective Temp., °F	86.1	86.7	84.2	85.6

*As obtained from ASHRAE Guide and Data Book - Fundamentals and Equipment, American Society of Heating, Refrigeration, and Air Conditioning Engineers, Inc., 1963, pps. 391-428.

**For 210-man aboveground shelter of Reference 2.

These results are similar to the agreement obtained with the transient analysis. If the steady-state shelter values of test #7 are compared to the time-average shelter values of the transient study for test #7, the results are within 2°F of each other. This shows that the steady-state shelter condition approximates the time-average shelter condition determined by the transient analysis.

The steady-state analysis with boundary heat losses was used to determine the psychrometric condition of the shelter as a function of the ventilation rate per occupant, the equipment and lighting load per occupant, the psychrometric conditions of the inlet air, and the heat loss coefficient, UA, see Figure 5, 6, and 7. The shelter dry-bulb temperature variation due to changes in the relative humidity of the inlet ventilation air is negligible (less than 0.01°F). This is not true of the effective temperature of the shelter and therefore, inlet air relative humidities of 15 and 80% are presented.

The main effect of the heat loss coefficient, UA, is to decrease the shelter dry-bulb and effective temperatures as the UA value increases. But, the temperature reduction decreases as the flow rate is increased, see Figure 8. Generally, less than 20% of the total energy input to the shelter is lost through the shelter boundaries; however, this percentage can become as high as 30-50% for external ambient dry-bulb temperature below 70°F and flow rates below 20 cfm/occupant.

Steady-State Analysis of Adiabatic Boundary Shelters

The adiabatic boundary shelter model differs from the nonadiabatic boundary shelter model in that it neglects any heat loss through the shelter boundary surfaces. This is not an unrealistic assumption, because the heat losses of the aboveground shelter can be a small percentage of the total heat input to the shelter. In the belowground shelter, a quasi-adiabatic boundary

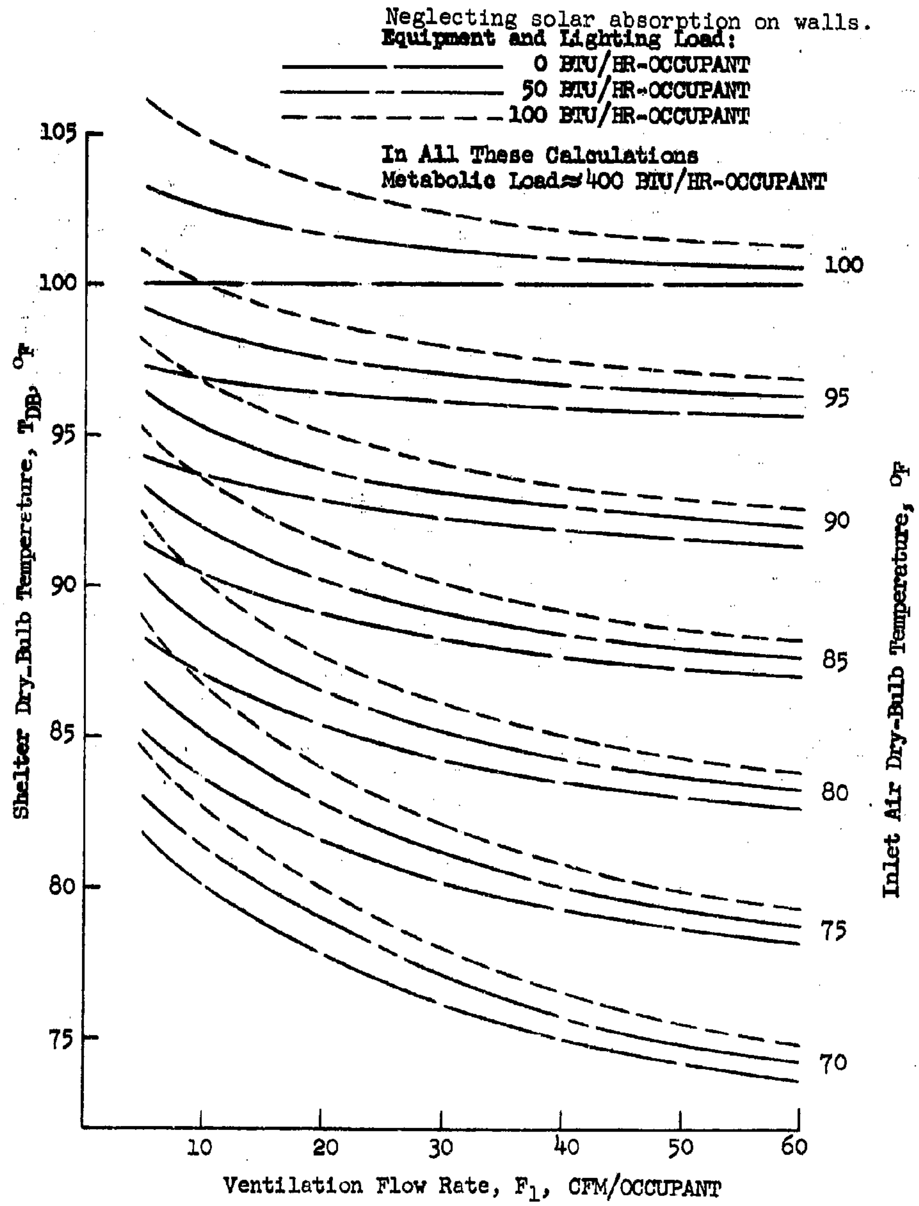


FIGURE 5 - NONADIABATIC BOUNDARY SHELTER DRY-BULB TEMPERATURES FOR ALL INLET AIR RELATIVE HUMIDITIES AND UA = 10 BTU/HR-°F-OCCUPANT

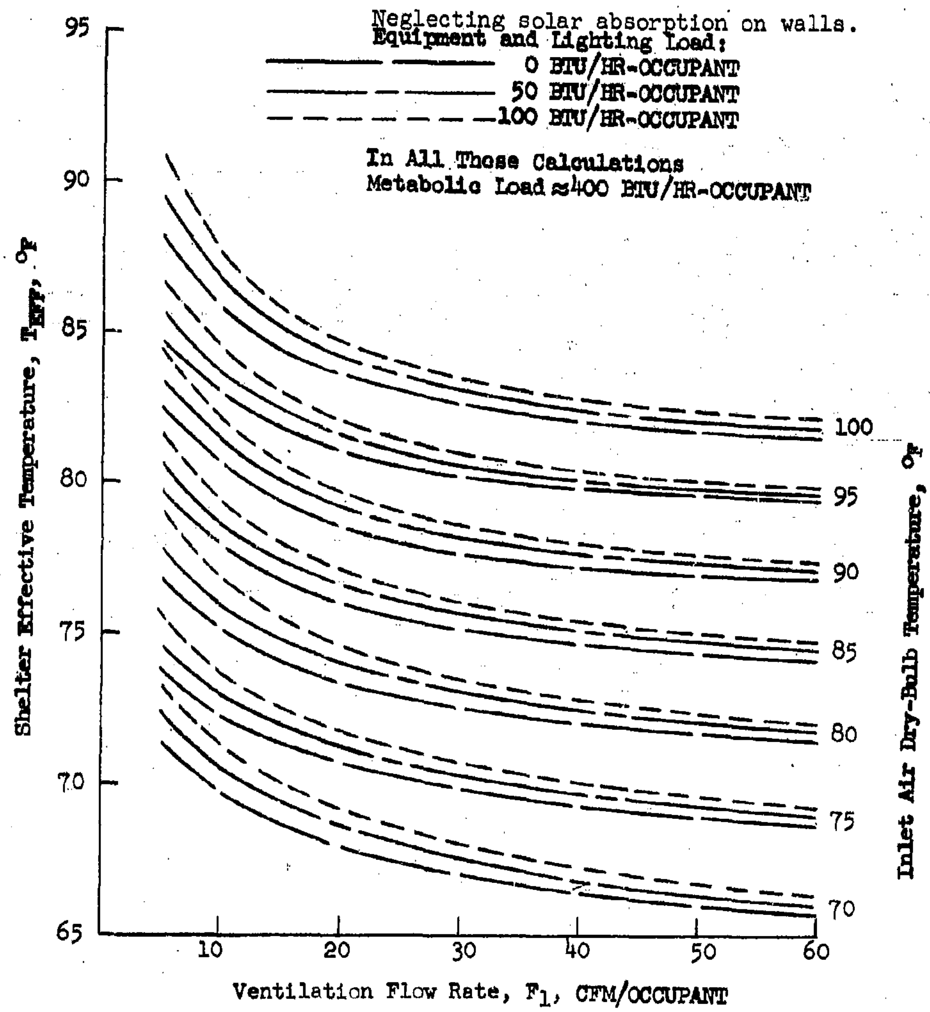


FIGURE 6 - NONADIABATIC BOUNDARY SHELTER EFFECTIVE TEMPERATURES FOR 15% INLET AIR RELATIVE HUMIDITY AND UA = 20 BTU/HR-°F-OCCUPANT

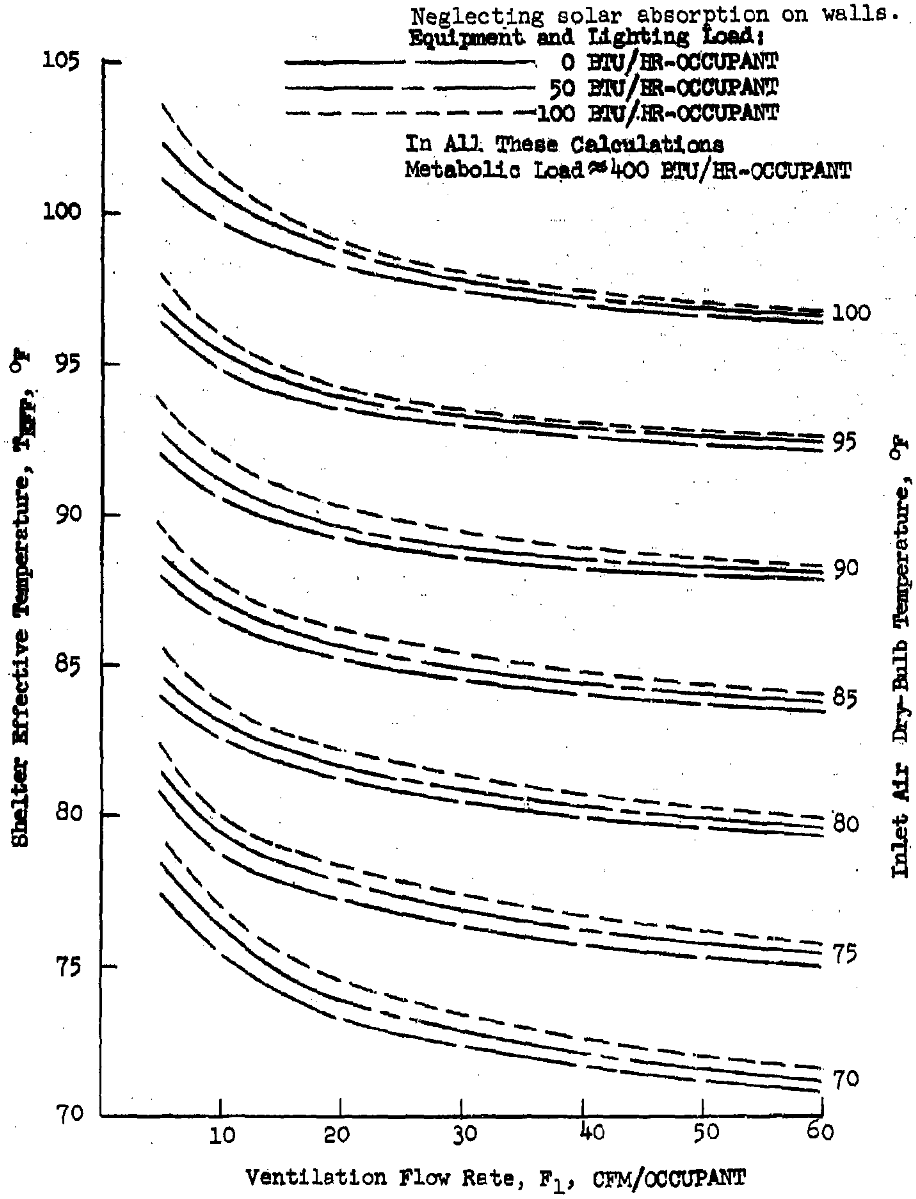


FIGURE 7 - NONADIABATIC BOUNDARY SHELTER EFFECTIVE TEMPERATURES FOR 80% INLET AIR RELATIVE HUMIDITY AND UA = 20 BTU/HR-°F-OCCUPANT

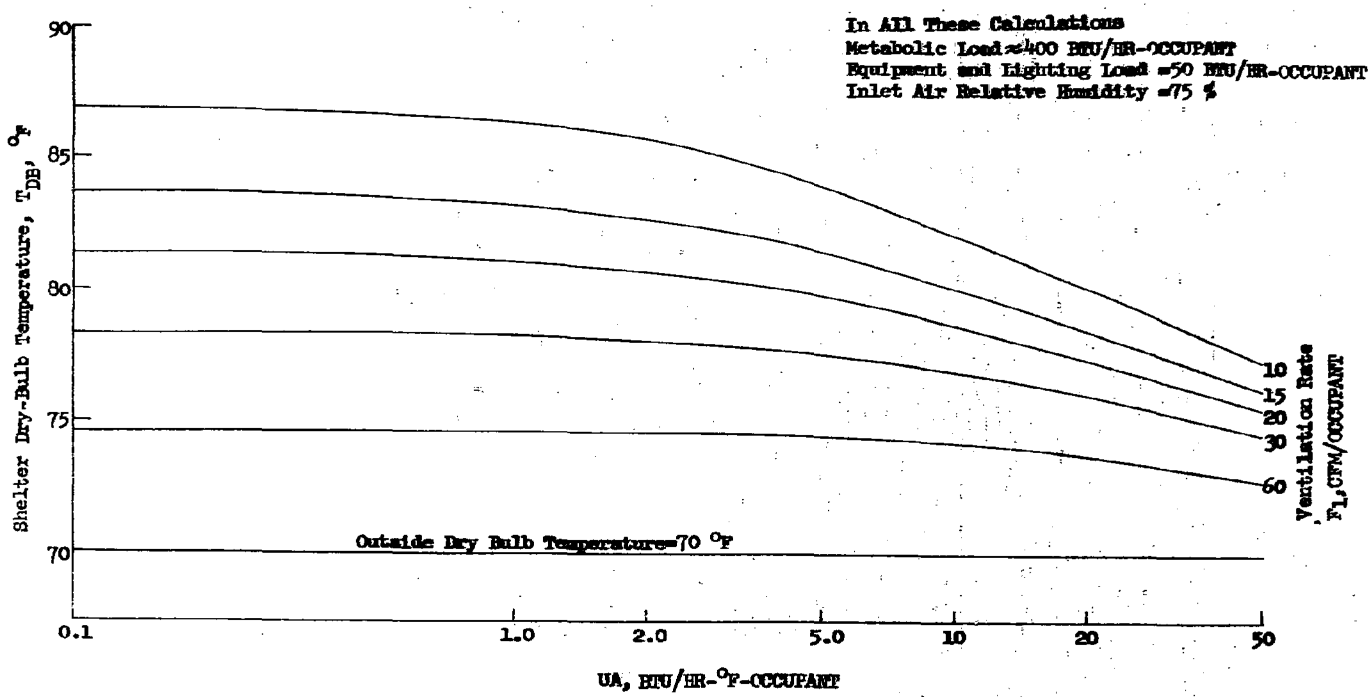


FIGURE 8 - INFLUENCE OF MAGNITUDE OF UA VALUE ON SHELTER DRY-BULB TEMPERATURE FOR VARIOUS VENTILATION RATES

condition is reached when the wall temperature approximates the shelter average dry-bulb temperature. For example, consider the Houston basement shelter tests. In these shelter tests the time-average soil temperature was 87.9°F whereas the time-average shelter dry-bulb temperatures varied from 82 to 87°F. When the Houston shelter is considered as an adiabatic boundary shelter by the steady-state analysis, the computed data agree with the test data to within 2°F in dry-bulb temperature and 1.5 °F in effective temperature, see Table 2.

TABLE 2

SUMMARY OF HOUSTON SHELTER TEST*

Observed Data	Test Nos. I	II	III	IV
Ventilation Rate, cfm/occupant	9.25	12.8	9.25	18.5
Average Inlet Dry-bulb Temp., °F	82	83	77	79
Average Inlet Effective Temp., °F	78	79	76	77
Average Inlet Relative Humidity	0.77	0.75	0.76	0.79
Average Shelter Dry-bulb Temp., °F	89.5	88.7	87	84
Average Shelter Effective Temp., °F	87	84.8	84	82
Values Predicted by Steady-State Adiabatic Boundary Analysis				
Shelter Dry-bulb Temp., °F	90.9	90.1	88.6	86.2
Shelter Effective Temp., °F	87.4	85.9	85.6	82.2

In test II, the steady-state and transient results agree to within 0.5°F when the shelter is considered to have adiabatic boundary walls. This again confirms the relationship of the time-average values of the transient analysis with the adiabatic boundary steady-state analysis.

The shelter's dry-bulb and effective temperatures were computed by the adiabatic boundary steady-state analysis for the same range of parameters used with the nonadiabatic boundary analysis, see Figures 9, 10, and 11. When these data are compared with the data for the nonadiabatic boundary shelter, the inlet air conditions that produce high rates of energy loss are found to

*For 290-man belowground basement shelter of Reference 4.

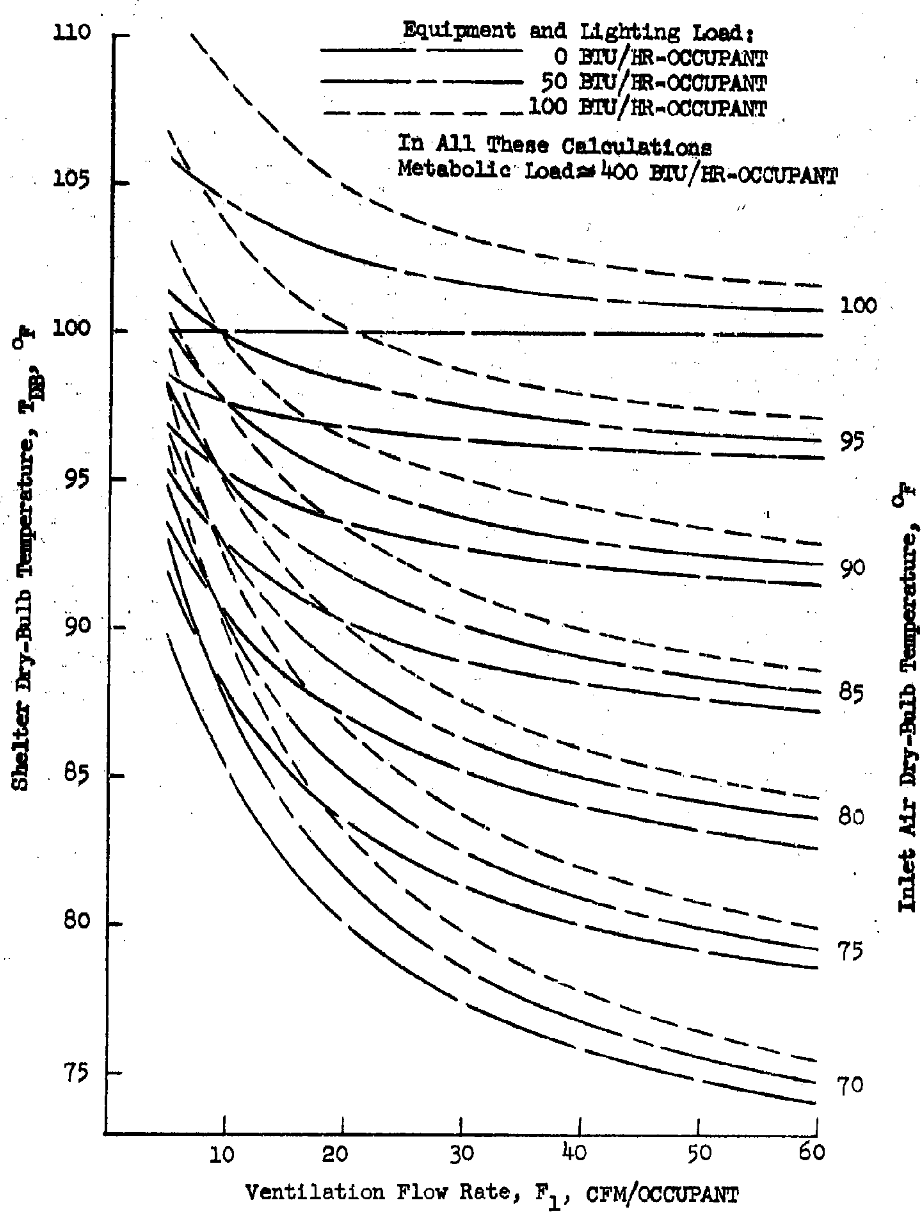


FIGURE 9 - ADIABATIC BOUNDARY SHELTER DRY-BULB TEMPERATURES FOR ALL INLET AIR RELATIVE HUMIDITIES

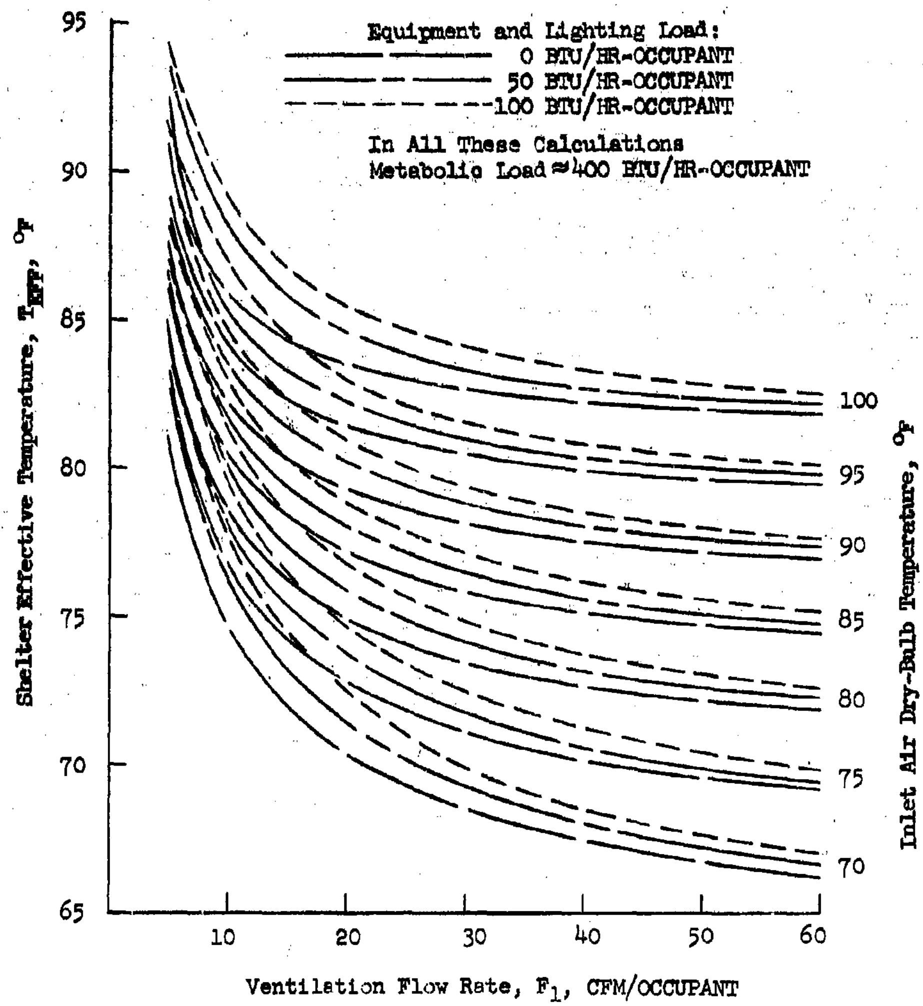


FIGURE 10 - ADIABATIC BOUNDARY SHELTER EFFECTIVE TEMPERATURES FOR 15% INLET AIR RELATIVE HUMIDITY

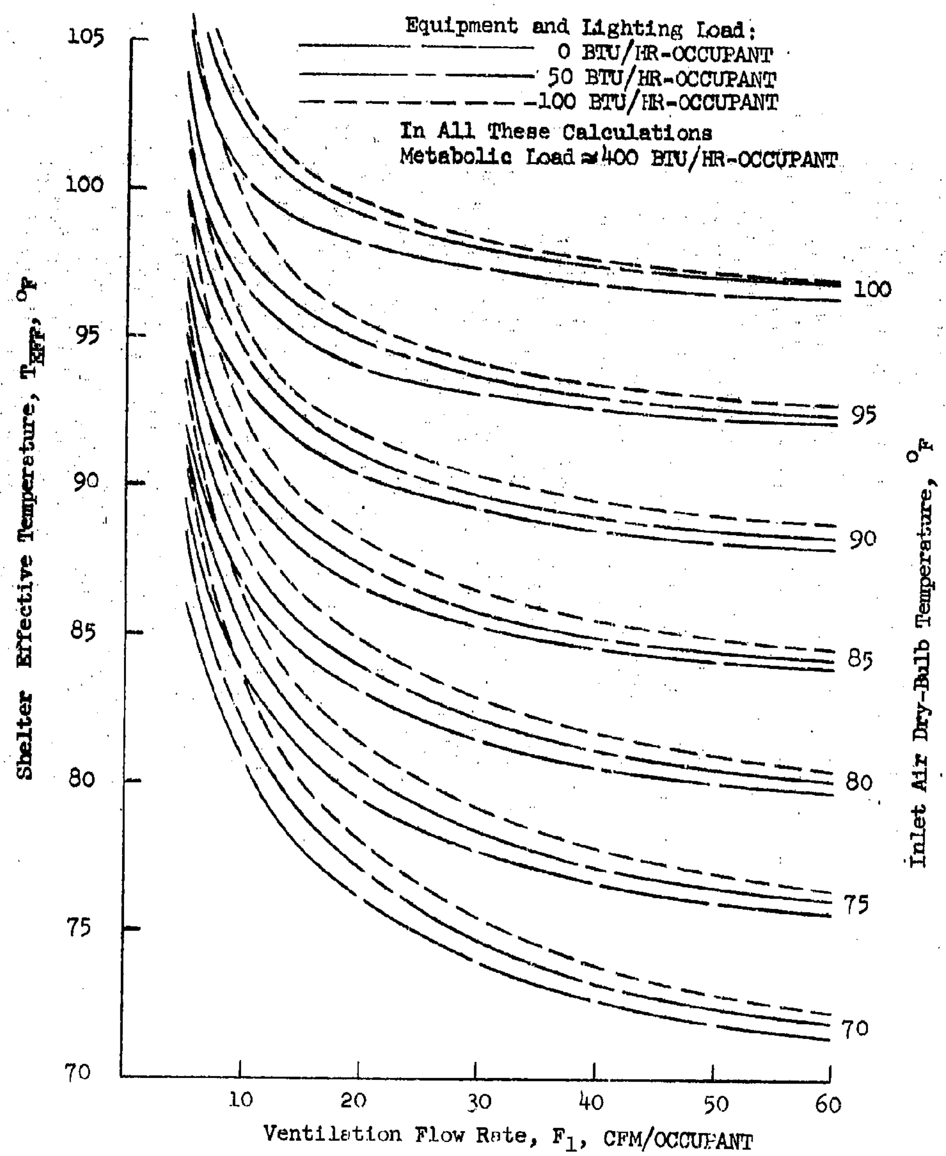


FIGURE 11 - ADIABATIC BOUNDARY SHELTER EFFECTIVE TEMPERATURES FOR 80% INLET AIR RELATIVE HUMIDITY

occur when energy loss is the least needed to control the shelter environment. For example, at inlet dry-bulb temperatures below 70°F, the adiabatic boundary shelter's effective temperature never exceeds 85°F except at flow rates of 6 cfm/ occupant and below, see Figures 10 and 11.

If the effective temperature index is accepted as the shelter habi-ability criteria, a psychrometric chart can be used as a means of determining the relationship between the psychrometric condition of the inlet air and the ventilation flow rate, see Reference 5. For instance, if an average effective temperature of 85°F is chosen as the habitability limit, the loci of the average psychrometric conditions of the inlet air that produce an 85°F effective temperature in the shelter can be plotted for various ventilation rates, see Figure 12.

Equipment and Lighting Load = Zero
Metabolic Load ≈ 400 Btu/hr-occupant
Steady-State Adiabatic Boundary
Shelter Model

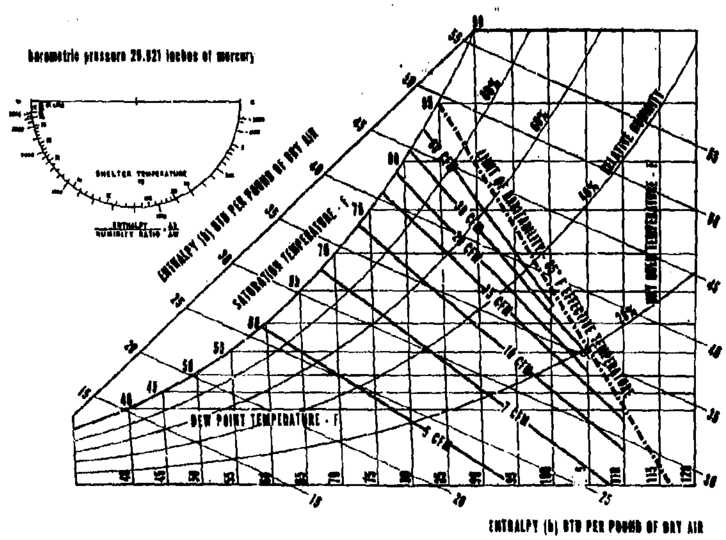


FIGURE 12 - VENTILATION RATES REQUIRED TO MAINTAIN AN AVERAGE EFFECTIVE TEMPERATURE OF 85°F

Local Ventilation Rates

In order to determine the ventilation rate required for any given shelter, weather design criteria must be selected. Several weather data studies are currently available upon which the weather design criteria could possibly be based (e.g., see References 6, 7, and 8), but the weather design criteria to be selected for a shelter must be based upon a detailed study of the relationship between the psychrometric state of the ambient weather and the effect that ventilation air from this ambient has on the shelter environment when actual weather data are considered. This relationship will be influenced by the interval of time chosen for the comparison. Possibly none of the available weather data studies will be applicable and a new set of criteria will have to be established. The MRD Division is presently engaged in a program for the Office of Civil Defense to study the relationship of periods of actual weather on shelter environment. In addition, more information must be gathered concerning the effect of environmental conditions on the human body; particularly, when these conditions are changing with time and the body is under a high level of emotional stress. However, this paper has shown that the regional ventilation requirements for shelters can be determined once the weather design criteria and habitability criteria are known.

CONCLUSIONS

The transient analysis is able to predict an aboveground shelter's instantaneous dry-bulb temperature to within 2°F and the shelter's instantaneous effective temperature to within 1°F. The time-average values of a shelter's dry-bulb and effective temperature are predicted by a steady-state analysis to within 2°F. Either of these analyses can be used to determine the environmental condition of a shelter with a reasonably high degree of accuracy. The steady-state analysis has established that the energy loss that can occur through the boundary surfaces of an aboveground shelter is generally less than 20% of the total thermal energy introduced into the shelter air during hot summer weather. All of these results indicate that the mechanism of heat loss through the boundary surfaces of an aboveground shelter cannot be depended upon to remove energy from the shelter during hot weather. At most, boundary surface heat loss should be regarded as a possible safety-factor in ventilation system design. It is therefore recommended that the ventilation systems for aboveground shelters be designed to remove the entire thermal load generated within the shelter.

The flow rate predicted by the analysis of a shelter without boundary surface heat loss is the maximum flow rate that can be required (assuming the solar radiation absroption effects on opaque shelter boundary surfaces are negligible*); and thus provides a means for establishing an upper limit on the size of the ventilation equipment for an aboveground shelter. The reasonable agreement between the calculations for a shelter without boundary surface heat loss and the shelter test data insures that the equipment size based upon this ventilation rate is not overly conservative.

The paper has shown that with metabolic head load data and weather design criteria the ventilation requirements for aboveground shelters (e.g., the shelters surveyed in the National Fallout Shelter Survey) can be determined analytically. The reliability of these predictions is primarily dependent upon the reliability of the metabolic and weather design data used in the calculation procedure.

*This assumption is presently under detailed evaluation by the MRD Division.

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APPENDIX A

DERIVATION OF EFFECTIVE TEMPERATURE EQUATION

DERIVATION OF EFFECTIVE TEMPERATURE EQUATION

Many sets of psychrometric conditions provide the human body with similar levels of physiological comfort. The effective temperature scale has been established as an empirically derived index of the various psychrometric conditions which produce similar comfort levels. The effective temperature is a function of the dry-bulb temperature, wet-bulb temperature, and velocity of the air in which a person resides. Generally, these data have been presented in nomographic form or by approximating equations. For the purposes of this study, the nomograms were inconvenient to use since they were not in equation form, and the existent equations were not of sufficient accuracy. As a result, an accurate mathematical expression for effective temperature was derived.

The derivation was based upon the ASHRAE nomogram* for effective temperature, see Figure A1. Because the ventilating air velocities in shelters is generally low, only the 20 ft/min flow velocity curve of the nomogram was considered. This eliminated the air velocity as a parameter in the determination of effective temperature. A schematic of the curve AA which represents the 20 ft/min flow velocity in the nomogram is shown in Figure A2. Curve AA is linearized by a straight line which intersects the wet-bulb (T_{WB}) and dry-bulb (T_{DB}) temperature scales at the points M and N respectively. By geometric similarity

$$\frac{P-Q}{N-O} = \frac{M-Q}{M-O} \qquad (A1)$$

and

$$\frac{P-Q}{S-T} = \frac{R-Q}{R-T} \qquad (A2)$$

*ASHRAE Guide and Data Book - Fundamentals and Equipment, American Society of Heating, Refrigeration, and Air Conditioning Engineers, Inc., 1963, p. 111

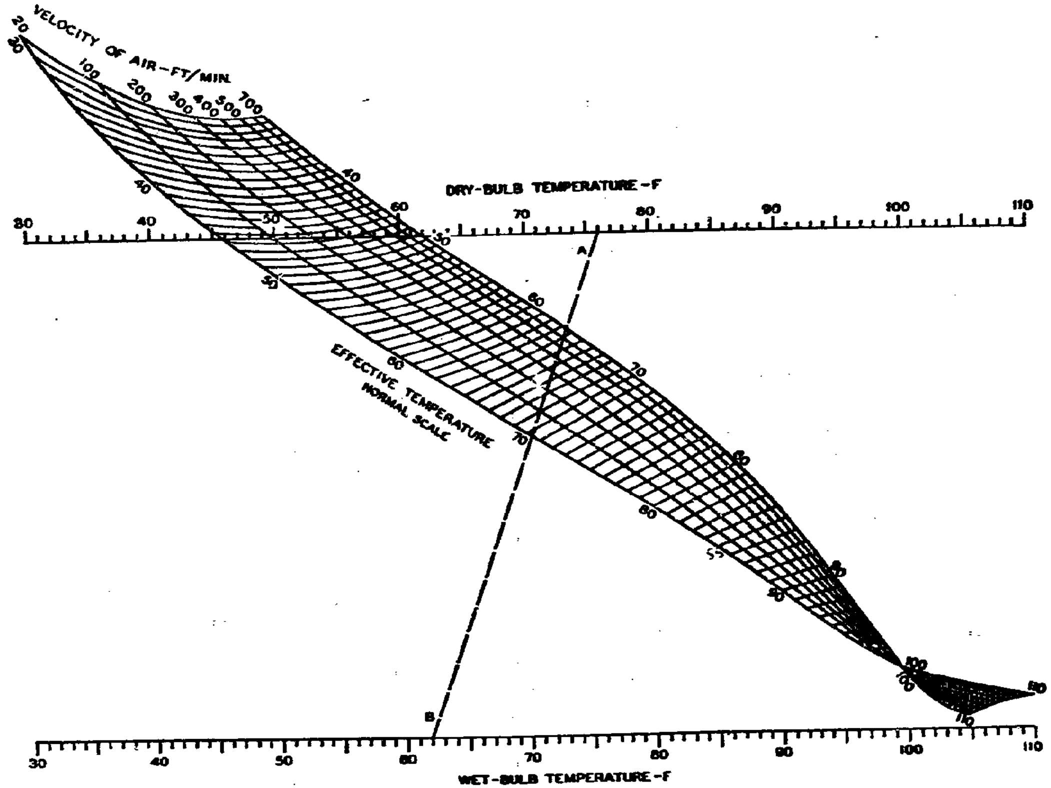

FIGURE A1 - ASHRAE EFFECTIVE TEMPERATURE NOMOGRAM

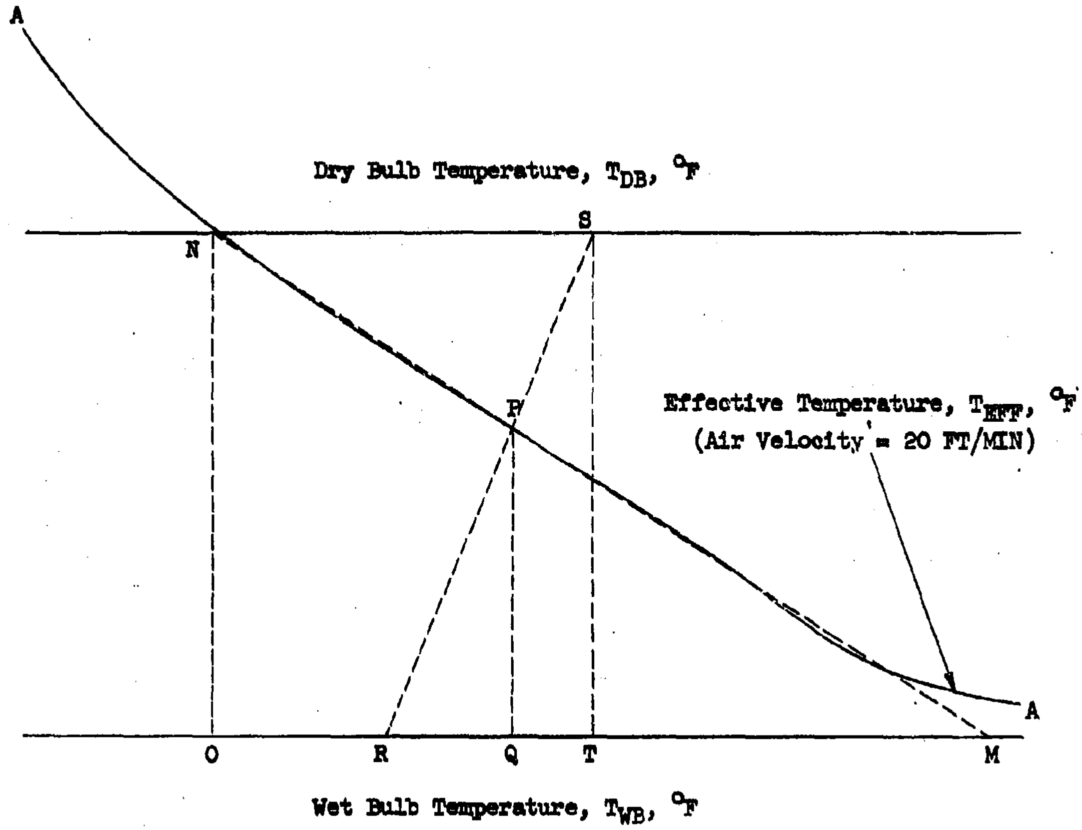

FIGURE A2 - SCHEMATIC OF NOMOGRAM OF EFFECTIVE TEMPERATURE, T_{EFF}

but $N - O = S - T$. Then

$$\frac{M-Q}{M-O} = \frac{R-Q}{R-T} \qquad \text{(A3)}$$

where

M	=	107.5°F	R	=	T_{WB}
N	=	45.2°F	P	=	T_{EFF}
O	=	45.2°F	Q	=	T_{EFF}
S	=	T_{DB}	R	=	T_{DB}

Substituting the above values into Equation (A3) yields

$$T_{EFF} = \frac{107.5\ (T_{DB} - T_{WB}) + 62.3\ (T_{WB})}{62.3 + (T_{DB} - T_{WB})} \qquad (A4)$$

This relationship is limited to low air velocities and is restricted to the temperature range of

$$45°F \leq T_{DB} \leq 110°F$$

and

$$30°F \leq T_{WB} \leq 100°F$$

The temperature range restrictions are imposed due to the fact that the T_{EFF} curve of the nomogram cannot be considered a straight line beyond these temperature limits. Table A1 shows that Equation (A4) has an average error of less than one percent.

TABLE A1 ERROR IN CALCULATED ERRECTIVE TEMPERATURES BY EQUATION (A4)

T_{DB}, °F	T_{WB}, °F	T_{eff}, cal'd by Equation (A4)	T_{eff}, read from Figure (A1)	Percent Error
110.0	98.0	99.4	99.0	0.45
110.0	90.0	94.2	94.0	0.21
110.0	30.0	73.5	74.0	0.68
90.0	80.0	83.9	83.9	0
90.0	60.0	75.5	75.6	0.13
90.0	40.0	70.0	70.0	0
80.0	60.0	71.5	71.5	0
80.0	40.0	66.3	66.3	0
80.0	30.0	64.7	64.3	0.62
70.0	60.0	66.6	66.5	0.15
70.0	50.0	63.9	64.0	0.15
45.0	30.0	45.1	45.0	0.22

The effective temperature values are correlated to the relative strain indicies with a 0.5 relative strain index being essentially an 85°F effective temperature, see Figure A3. Almost all people are comfortable at zero relative strain index and physical failure is rapid and severe at 1.0

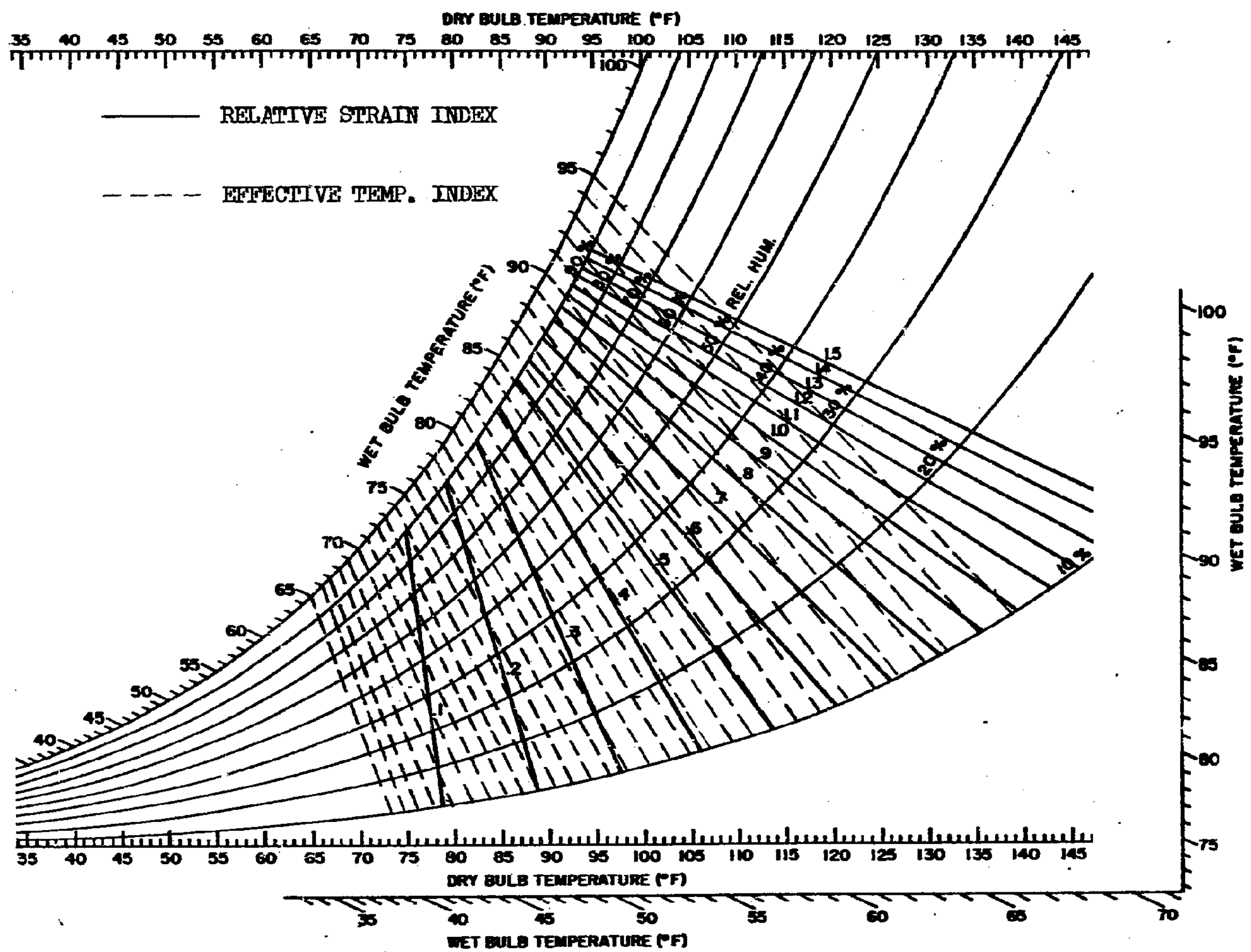

Figure A3 - RELATIONSHIP OF EFFECTIVE TEMP AND RELATIVE STRAIN INDICES relative strain index.* This comparison illustrates the convertability of the effective temperature index to other indices of physiological comfort.

*D. H. Lee and A. Henschel "Evaluation of Thermal Environment in Shelters", U.S. Department of Health, Education, and Welfare, TR-8, August, 1963

APPENDIX B

ANALYTICAL MODEL

B.1 DERIVATION OF ANALYTICAL SHELTER MODEL

The analytical model for a shelter is formulated with the philosophy that whether a shelter is above or below ground and whether it is single story or multi-story, the shelter can be represented by a single mathematical model. Furthermore, the model is developed with the idea that it should be the simplest model that can be devised and still adequately explain the phenomena. In accord with this philosophy, the assumptions are made that

1. the air within the shelter is so completely mixed that all of the shelter air is at one psychrometric condition,
2. the convective heat transfer coefficient for each external boundary surface of the shelter is not a function of temperature and has a constant value over the surface,
3. the walls and floors which are internal to the shelter volume are at the dry-bulb temperature of the shelter air,
4. the radiative energy interchanges within the shelter can be neglected,
5. the solar direct and indirect radiative input to the shelter through windows and the equipment and lighting heat loads in the shelter can be grouped together as one time dependent load factor which is termed the thermal load,
6. the ventilating air exhausted from the shelter is at the psychrometric condition of the shelter air,
7. the effects of condensation on the walls, floors, and ceilings of the shelter can be neglected, and
8. the thermal-physical properties of the structural materials are not temperature dependent.

The model of the shelter is established by these assumptions. Thus the shelter is idealized as an enclosed volume in which sensible heat, latent heat, solar heat, equipment heat, and ventilating air are introduced and from which air is exhausted and energy is lost. The governing principles for such a model are the conservation of energy and the conservation of the masses of dry air and water vapor.

The conservation of energy requires that

$$\begin{aligned} &\begin{bmatrix}\text{the rate of change of enthalpy}\\ \text{in the ventilating air}\end{bmatrix} + \begin{bmatrix}\text{the rate of change of enthalpy}\\ \text{in the shelter air}\end{bmatrix} \\ + &\begin{bmatrix}\text{the rate of metabolic heat}\\ \text{input by the shelter occupants}\end{bmatrix} + \begin{bmatrix}\text{the rate of thermal}\\ \text{load to the shelter}\end{bmatrix} \\ + &\begin{bmatrix}\text{the rate of energy transfer across}\\ \text{the shelter boundary surfaces}\end{bmatrix} = 0 \end{aligned} \qquad \text{(B1)}$$

and integrating Equation (B1) over the time increment $\Delta\tau$

$$(H_1 - H_2) + (H_{S,1} - H_{S,2}) + Q_M + Q_T - Q_B = 0 \qquad \text{(B2)}$$

where:

H_1 = enthalpy of ventilating air entering the shelter, Btu

H_2 = enthalpy of ventilating air leaving the shelter, Btu

$H_{S,1}$ = enthalpy of shelter air at beginning of time increment $\Delta\tau$, Btu

$H_{S,2}$ = enthalpy of shelter air at end of time increment $\Delta\tau$, Btu

Q_M = energy due to metabolism of shelter occupants, Btu

Q_T = energy input due to thermal load (see assumption #5, p. B2), Btu

Q_B = energy loss or gain through shelter boundary surfaces, Btu

The conservation of the mass of water vapor necessitates that

$$\begin{bmatrix}\text{the rate of change of water}\\ \text{vapor in the ventilating air}\end{bmatrix} + \begin{bmatrix}\text{the rate of change of water}\\ \text{vapor in the shelter air}\end{bmatrix} + \begin{bmatrix}\text{the rate of water vapor}\\ \text{introduced by the shelter occupants}\end{bmatrix} = 0 \tag{B3}$$

and integrating Equation (B3) over the time increment $\Delta\tau$

$$(M_{V,1} - M_{V,2}) + (M_{V,S,1} - M_{V,S,2}) + M_{V,M} = 0 \tag{B4}$$

where:

$M_{V,1}$ = mass of water vapor in the entering ventilating air, lb

$M_{V,2}$ = mass of water vapor in the exhausting ventilating air, lb

$M_{V,S,1}$ = mass of water vapor in the shelter at the beginning of the time increment $\Delta\tau$, lb

$M_{V,S,2}$ = mass of water vapor in the shelter at the end of time increment $\Delta\tau$, lb

$M_{V,M}$ = mass of water vapor introduced by the shelter occupants, lb

The conservation of the mass of dry air demands that

$$\begin{bmatrix}\text{the rate of change of dry}\\ \text{air in the ventilating air}\end{bmatrix} + \begin{bmatrix}\text{the rate of change of dry}\\ \text{air in the shelter air}\end{bmatrix} = 0 \tag{B5}$$

and integrating over the time increment $\Delta\tau$

$$(M_{a,1} - M_{a,2}) + (M_{a,S,1} - M_{a,S,2}) = 0 \tag{B6}$$

where:

$M_{a,1}$ = mass of dry air in the entering shelter air, lb

$M_{a,2}$ = mass of dry air in the exhausting shelter air, lb

$M_{a,S,1}$ = mass of dry air in the shelter at the beginning of the time increment, lb

$M_{a,S,2}$ = mass of dry air in the shelter at the end of the time increment, lb

Denoting

$$\Delta Q = H_1 + H_{S,1} + Q_M + Q_T - Q_B \tag{B7}$$

$$M_{V,0} = M_{V,1} + M_{V,S,1} + M_{V,M} \tag{B8}$$

$$M_{a,0} = M_{a,1} + M_{a,S,1} \tag{B9}$$

and substituting Equation (B7) through (B9) into Equations (B2), (B4) and (B6) gives

$$\Delta Q = H_{S,2} + H_2 \tag{B10}$$

$$M_{V,0} = M_{V,2} + M_{V,S,2} \tag{B11}$$

$$M_{a,0} = M_{a,2} + M_{a,S,2} \tag{B12}$$

where:

$$H_{S,2} = M_{a,S,2}h_{a,S,2} + M_{V,S,2}h_{V,S,2} \tag{B13}$$

$$H_2 = M_{a,2}h_{a,2} + M_{V,2}h_{V,2} \tag{B14}$$

From the assumption that the exhaust air has the same psychrometric condition as the shelter air

$$h_{a,2} = h_{a,S,2} \tag{B15}$$

and

$$h_{V,2} = h_{V,S,2} \tag{B16}$$

With Equations (B11) to (B16) substituted into Equation (B10)

$$\Delta Q = M_{a,0}h_{a,S,2} + M_{V,0}h_{V,S,2} \tag{B17}$$

The specific enthalpies of dry air and water vapor are given by

$$h_a = 0.24\ (T_{DB} + 459.69) \tag{B18}$$

and

$$h_V = 1061 + 0.444\ (T_{DB}) \tag{B19}$$

$$\text{for } 32°\text{F} \leq T_{DB} \leq 150°\text{F}$$

where:

T_{DB} = dry-bulb temperature, °F

Combining Equations (B17) to (B19) and solving for the dry-bulb temperature results in

$$T_{DB,2} = \frac{\Delta Q - 857\ M_{V,0}}{0.444\ M_{V,0} + 0.24\ M_{a,0}} \tag{B20}$$

where:

$T_{DB,2}$ = dry-bulb temperature of shelter air at end of time increment $\Delta\tau$, °F

The following relationships are evident:

$$M_{a,2} = 60\ F_2\ \rho_{a,2}\Delta\tau \tag{B21}$$

$$M_{V,2} = 60\ F_2\ \rho_{V,2}\Delta\tau \tag{B22}$$

$$M_{a,S,2} = V\ \rho_{a,S,2} \tag{B23}$$

and

$$M_{V,S,2} = V\ \rho_{V,S,2} \tag{B24}$$

where:

V = shelter volume, ft^3

$\Delta\tau$ = time increment, hr

$\rho_{a,2}$ = density of dry air leaving shelter, lb/ft^3

$\rho_{V,2}$ = density of water vapor leaving shelter, lb/ft^3

$\rho_{a,S,2}$ = density of dry air in shelter at end of time increment, lb/ft^3

$\rho_{V,S,2}$ = density of water vapor in shelter at end of time increment lb/ft^3

F_2 = volumetric flow rate of exhaust air, ft^3/min

but by assumption

$$\rho_{a,2} = \rho_{a,S,2} \tag{B25}$$

and

$$\rho_{V,2} = \rho_{V,S,2} \tag{B26}$$

Substituting Equation (B21) through (B26) into Equation (B11) and (B12) yields

$$M_{V,0} = \rho_{V,2} (60 F_2 \Delta\tau + V) \tag{B27}$$

and

$$M_{a,0} = \rho_{a,2} (60 F_2 \Delta\tau + V) \tag{B28}$$

When Equations (B27) and (B28) are solved for F_2, they result in

$$F_2 = \frac{M_{a,0} - \rho_{a,2} V}{60\Delta\tau \ \rho_{a,2}} \tag{B29}$$

$$= \frac{M_{V,0} - \rho_{V,2} V}{60\Delta\tau \ \rho_{V,2}} \tag{B30}$$

The densities of the dry air and water vapor are assumed to obey the perfect gas law. Thus;

$$\rho_V = \frac{P_V}{R_V(T_{DB} + 459.69)} \tag{B31}$$

and

$$\rho_a = \frac{P_B - P_V}{R_a(T_{DB} + 459.69)} \tag{B32}$$

where:

P_B = barometric pressure, lb/ft^2

P_V = partial pressure of water vapor, lb/ft^2

R_V = gas constant for water vapor, ft-lb/lb_{mole}-°R

R_a = gas constant for dry air, ft-lb/lb_{mole}-°R

The partial pressure of water vapor is expressed by

$$P_V = r \, P_S \tag{B33}$$

where:

r = relative humidity

P_S = saturation pressure of water vapor, lb/ft^2

$$P_S = 5.132e^{0.0329(T_{DB})} \tag{B34}$$

$$\text{for} \quad 32°F \leq T_{DB} \leq 150°F$$

which is an analytical expression for the tabulated values of saturated vapor pressures as a function of dry-bulb temperature (Ref. 8).

From Equation (B30) through (B33) with

$$R_a = 53.35 \text{ ft-lb/lb}_{mole}\text{-°R}$$

and

$$R_V = 85.71 \text{ ft-lb/lb}_{mole}\text{-°F}$$

the following expressions can be obtained:

$$P_V = r \left[5.132e^{0.329(T_{DB})}\right] \tag{B35}$$

$$\rho_V = \frac{1}{(T_{DB} + 459.69)} \left[0.05987\, r\, e^{0.0329(T_{DB})}\right] \tag{B36}$$

and

$$\rho_a = \frac{1}{(T_{DB} + 459.69)} \left[0.018744 P_B - 0.0962\, r\, e^{0.0329(T_{DB})}\right] \tag{B37}$$

Equating Equation (B27) and (B28) gives

$$\frac{M_{a,0}}{\rho_{a,2}} = \frac{M_{V,0}}{\rho_{V,2}} \tag{B38}$$

Evaluating Equations (B36) and (B37) at the shelter dry-bulb temperature, $[T_{DB,2}]$, and substituting the results into Equation (B38) gives the partial pressure of the water vapor $[P_V]$ as

$$P_V = \frac{P_B}{1+0.6224\left(\frac{M_{a,0}}{M_{V,0}}\right)} \tag{B39}$$

And from Equation (B33), the relative humidity of the shelter at the end of the time increment is given by

$$r = \frac{P_V}{P_S} \tag{B40}$$

Substituting Equations (B34) and (B39) into Equation (B40) results in

$$r = \frac{P_B}{5.132e^{(0.0329(T_{DB}))}\left[1 + 0.6224\,\frac{M_{a,0}}{M_{V,0}}\right]} \tag{B41}$$

With these equations, the psychrometric conditions within the shelter can be determined as a function of time through the use of the following procedure.

1. Determine the psychrometric conditions of the air introduced into the shelter and the air within the shelter along with the heat inputs and losses of the shelter for the time interval $\Delta\tau$

2. Compute the quantities ΔQ, $M_{V,0}$, and $M_{a,0}$ from Equations (B7), (B8), and (B9) respectively.

3. Assume that these quantities do not change over the time interval $\Delta\tau$, and compute the dry-bulb temperature of the shelter at the end of the time interval from Equation (B20).

4. Calculate the relative humidity of the shelter air at the end of the time interval from Equation (B41).

5. Set the psychrometric conditions of the shelter at the end of the time increment equal to those in the shelter for the beginning of the next increment, and repeat the entire procedure.

By the continuous application of this procedure, the shelter's psychrometric condition can be obtained as a function of time for any time period. The computation method that has been developed constitutes a transient analysis of the shelter environment under the influence of time varying parameters.

The shelter's psychrometric condition is described in the analysis by its dry-bulb temperature and relative humidity. Instead, the dry-bulb and wet-bulb or effective temperatures can be used. The wet-bubl temperature is determined from the Carrier equation.*

$$P_V = P_S' - \frac{(P_B - P_S')(T_{DB} - T_{WB})}{2800.0 - 1.3\ (T_{WB})} \tag{B42}$$

* J. H. Carpenter, "Fundamentals of Psychrometrics", Carrier Corporation, Technical Note T 200-20, Syracuse, New York, 1962, p. 12.

where:

P_S' = saturation pressure at wet-bulb temperature, lb/ft^2

T_{WB} = wet-bulb temperature, °F

with P_S' evaluated by Equation (B34)

$$P_S' = 5.132 \, e^{0.0329(T_{WB})} \tag{B43}$$

and P_V obtained from Equation (B39). The results is a transcendental equation that can be solved for the wet-bulb temperature, T_{WB}. When the value of the wet-bulb temperature is known, the effective temperature can be determined from equation (A4).

$$T_{EFF} = \frac{107.5\,(T_{DB} - T_{WB}) + 62.3\,(T_{WB})}{62.3 + (T_{DB} - T_{WB})} \tag{B44}$$

As mentioned in Appendix A, this relationship is limited to low air velocities and is restricted to the temperature range of

$$45°F \leq T_{DB} \leq 110°F$$

and

$$30°F \leq T_{WB} \leq 100°F$$

The heat loss or gain of the shelter boundary, Q_B, over a time interval $\Delta\tau$ is determined by the temperature of the inner surface of the boundary, T_1. In the computations, the value of T_1 is obtained from the temperature distribution that existed through the boundary during the previous time increment. This temperature distribution is deduced from a transient analysis of the energy transfer in the boundary. In order to accomplish this analysis, the boundary is divided into a finite number of slabs of thickness ΔX, except for the inner and outer surfaces which are made into slabs of thickness $\Delta X/2$, with each slab assumed to be at a single temperature. This temperature is assigned to the midpoint of each slab, except for the innermost and outermost slabs which are assigned temperatures at the external surfaces of the slab (see Figure B1). These locations of slab temperature are termed nodal points. The external nodal points of the boundary transfer energy by convection with surrounding air and by conduction with the next internal nodal point. All of the rest of the nodal points transfer energy by conduction with the two adjacent nodal points. The energy balance about an internal nodal point m is

$$\begin{bmatrix}\text{energy conducted}\\ \text{to point m from}\\ \text{point (m-1)}\end{bmatrix} - \begin{bmatrix}\text{energy conducted to}\\ \text{point (m+1) to}\\ \text{point m}\end{bmatrix} = \begin{bmatrix}\text{energy stored in}\\ \text{the slab of point m}\end{bmatrix} \tag{B45}$$

or

$$-kA\,\frac{(T_m - T_{m-1})}{\Delta\chi} + kA\,\frac{(T_{m+1} - T_m)}{\Delta\chi} = \frac{\Delta\chi\, A\rho C_p (T_m{}' - T_m)}{\Delta\tau} \tag{B46}$$

and the temperature at the nodal point is

$$T_m{}' = B_1(T_{m-1} + T_{m+1}) + (1 - 2B_1)T_m \tag{B47}$$

with

$$B_1 \leq \frac{1}{2} \tag{B48}$$

where:

$B_1 = \dfrac{\alpha\Delta\tau}{\Delta\chi^2}$

$\alpha = \dfrac{k}{\rho C_p}$

k = thermal conductivity of composite boundary material, Btu/hr-ft-°F

ρ = density of composite boundary material, lb/ft^3

C_p = specific heat of composite boundary material, Btu/lb-°F

$\Delta\chi$ = thickness of boundary slab, ft

T_m = temperature of nodal point m at beginning of time increment, °F

T_{m-1} = temperature of nodal point m-1 at beginning of time increment, °F

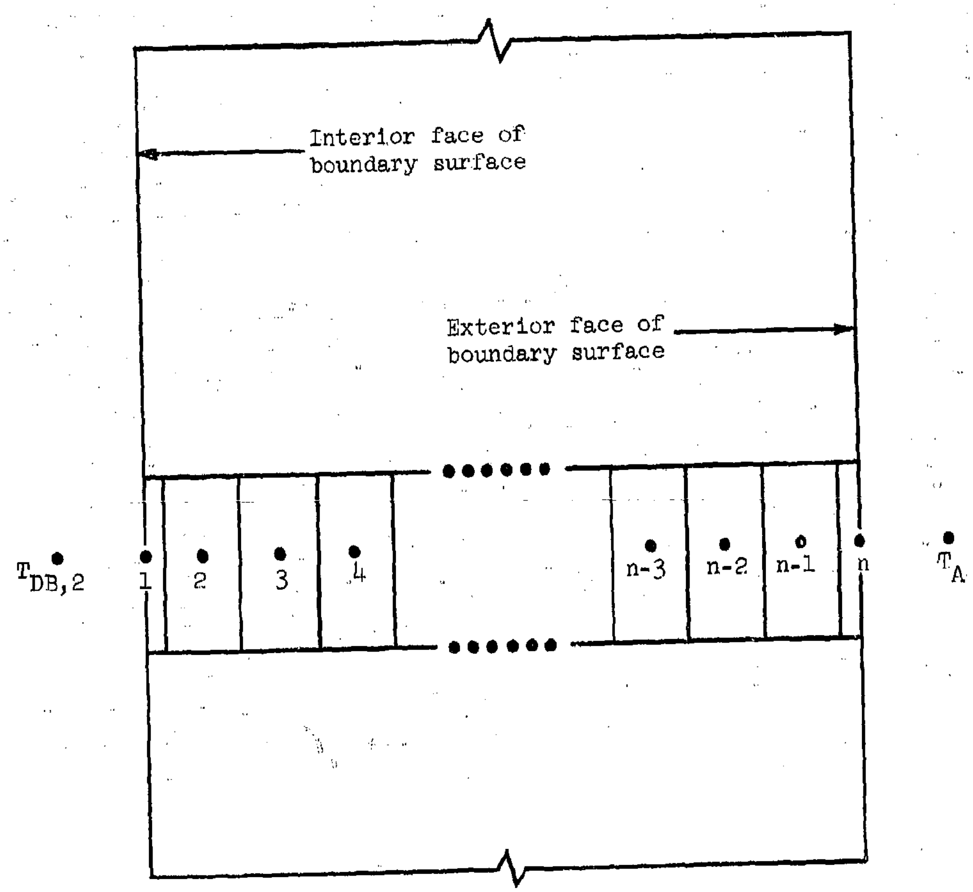

Figure . B1 ARRANGEMENT OF NODAL POINTS IN SHELTER BOUNDARY SURFACE

T_{m+1} = temperature of nodal point m+1 at beginning of time increment, °F

T_m' = temperature of nodal point m at end of time increment, °F

The energy balance about the inner surface of the boundary is

$$\begin{bmatrix}\text{energy convected}\\ \text{from shelter air}\\ \text{to boundary}\end{bmatrix} - \begin{bmatrix}\text{energy conducted to}\\ \text{nodal point 2 from}\\ \text{nodal point 1}\end{bmatrix} = \begin{bmatrix}\text{energy stored in}\\ \text{the slab at}\\ \text{nodal point 1}\end{bmatrix} \quad \text{(B49)}$$

or

$$h_i A(T_{DB,2} - T_1) + kA\frac{(T_2 - T_1)}{\Delta\chi} = \frac{\Delta\chi}{2} A \frac{\rho C_p}{\Delta\tau}(T_1' - T_1) \quad \text{(B50)}$$

and the temperature at the inner boundary surface is

$$T_1' = B_2 B_3 T_{DB,2} + B_3 T_2 + (1 - B_3 - B_2 B_3)T_1 \quad \text{(B51)}$$

$$\text{with } B_3(B_2 + 1) \leq 1 \quad \text{(B52)}$$

where:

$B_2 = \dfrac{h_i \Delta\chi}{k}$

$B_3 = 2B_1$

h_i = heat transfer coefficient on the inner surface of the boundary, Btu/hr-ft^2-°F

$T_{DB,2}$ = temperature of shelter at beginning of time increment, °F

T_1 = temperature of nodal point at inner surface of boundary at beginning of time increment, °F

T_2 = temperature of nodal point 2 at beginning of time increment, °F

T_1' = temperature of nodal point at inner surface of boundary at end of time increment, °F

The energy balance about the outer surface of the boundary n is

$$\begin{bmatrix}\text{energy conducted}\\ \text{from (n-1) nodal}\\ \text{point to outer}\\ \text{surface point n}\end{bmatrix} - \begin{bmatrix}\text{energy convected}\\ \text{from outer surface}\\ \text{point n to exter-}\\ \text{nal ambient air}\end{bmatrix} + \begin{bmatrix}\text{energy absorbed}\\ \text{from solar radi-}\\ \text{ation in the slab}\\ \text{at the outer}\\ \text{surface}\end{bmatrix} = \begin{bmatrix}\text{energy stored}\\ \text{in the slab}\\ \text{at the outer}\\ \text{surface}\end{bmatrix} \quad \text{(B53)}$$

or $$-kA\,\frac{(T_n - T_{n-1})}{\Delta\chi} - h_o A (T_n - T_A) + \psi Q_S = \frac{\Delta\chi}{2} A \, \frac{\rho C_p}{\Delta\tau} (T_n' - T_n) \quad \text{(B54)}$$

and the temperature at the outer boundary surface is

$$T_n' = B_3 T_{n-1} + B_4 B_3 T_A + (1 - B_3 - B_4 B_3) T_n + \frac{B_3 \alpha \Delta\chi}{k} Q_S \quad \text{(B55)}$$

$$\text{with } B_3(B_4 + 1) \le 1 \quad \text{(B56)}$$

where:

$B_4 = \dfrac{h_o \Delta\chi}{k}$

h_o = heat transfer coefficient on the outer surface of the boundary, Btu/hr-ft^2-°F

Q_S = intensity of solar radiation for shelter location and given calender date per unit area, Btu/hr-ft^2

T_n = temperature of nodal point n at outer surface of boundary at beginning of time increment, °F

T_{n-1} = temperature of nodal point n-1 at beginning of time increment, °F

T_A = temperature of external ambient air at beginning of time increment, °F

T_n' = temperature of nodal point n at outer surface of boundary at end of time increment, °F

ψ = absorptance of outer slab surface for solar radiation

The boundary surface heat loss as defined by Equations (B47), (B51), and (B55) is applicable to the one dimensional heat transfer from a boundary surface. If the boundary surfaces of a shelter are large, corner effects are negligible and each boundary surface can be considered to be conducting energy from or to the shelter uni-directionally. However, the problem in solving for the heat energy loss or gain from the shelter boundary surfaces is dependent upon the designation of a temperature T_A in Equation (B55) and the properties of the boundary surface, i.e., density (ρ), thermal conductivity (k), specific heat (c_p), and thickness (λ) with $\Delta\chi = \frac{\lambda}{n-1}$ where n = number of nodal points. To simplify the analysis, the shelter boundary surfaces are grouped together to form one slab surface exposed to the temperature of the shelter on one side, and the temperature T_A on the other side. The procedure of replacing all of the separate boundary surfaces by one slab surface is based upon the determination of area weighted average values for the various properties of the boundary surface. The property values of each boundary surface are based upon thickness weighted average property values of the materials that compose each of the boundary surfaces. For example, for any boundary surface property X, the area weighted average value of property X for the slab surface is given by

$$\bar{X} = [\sum_{p=1}^{r(j)} \sum_{j=1}^{m} (\frac{A_j}{\lambda_j}) (\lambda_p X_p)] / \bar{A} \qquad (B57)$$

where:

A_j = surface area of boundary surface j

m = number of boundary surfaces

X_p = property X of the material p in the boundary surface j

λ_p = thickness of the material p in the boundary surface j

r(j) = number of materials in boundary surface j

$$\lambda_j = \sum_{p=1}^{r(j)} \lambda_p$$

$$\bar{A} = \sum_{j=1}^{m} A_j$$

so that

$$\bar{\rho} = [\sum_{p=1}^{r(j)} \sum_{j=1}^{m} (\frac{A_j}{\lambda_j}) (\lambda_p \rho_p)] / \bar{A} \qquad (B58)$$

$$\bar{k} = [\sum_{p=1}^{r(j)} \sum_{j=1}^{m} (\frac{A_j}{\lambda_j}) (\lambda_p k_p)] / \bar{A} \qquad (B59)$$

$$\bar{C}_p = \left[\sum_{p=1}^{r(j)} \sum_{j=1}^{m} \left(\frac{A_j}{\lambda_j}\right) (\lambda_p (C_p)_j) \right] / \bar{A} \tag{B60}$$

and

$$\bar{\lambda} = \left[\sum_{j=1}^{m} A_j \lambda_j \right] / \bar{A} \tag{B61}$$

The values $\bar{\rho}$, $\bar{k}$, $\bar{C}_p$, and $\bar{\lambda}$ determine the property values of the composite boundary surface slab.

In general, the exterior sides of shelter boundary surfaces are exposed to three types of environments. The boundary surface can be exposed to the ambient weather (e.g., an outside wall), to the soil (e.g., an underground wall, the floor), or to a space interior to the structure but exterior to the shelter (e.g., a first floor shelter ceiling exposed to a second floor space of the building). In each of these situations, the value of T_A for each boundary surface will be different. In general, the area weighted average value of T_A would be

$$\bar{T}_A = \frac{\sum_{j=1}^{m} A_j (T_A)_j}{\sum_{j=1}^{m} A_j} \tag{B62}$$

where:

$(T_A)_j$ = temperature to which the exterior side of boundary surface j is exposed

Letting

$$p_j = \frac{A_j}{\sum_{j=1}^{m} A_j} \quad \text{with } j = 1,2,\ldots, m \tag{B63}$$

then

$$\bar{T}_A = \sum_{j=1}^{m} p_j (T_A)_j \tag{B64}$$

With the fact that the exterior side of the boundary surface can be exposed to only three types of environments, then

$$\bar{T}_A = p_o(T_A)_o + p_S(T_A)_S + p_i(T_A)_i \quad \text{with } i = 1,2,\ldots,q. \tag{B65}$$

where:

p_o = percentage of shelter boundary surfaces exposed to the ambient weather temperature $(T_A)_o$

p_S = percentage of shelter boundary surfaces exposed to soild at the temperature $(T_A)_S$

p_i = percentage of shelter boundary surfaces exposed to each of the interior space temperatures $(T_A)_i$ for each of the q interior spaces.

However, experience and experimental test results have shown that the temperature values of the soil and interior areas adjacent to the shelter can be closely approximated by

$$(T_A)_S = \frac{T_S + T_{SE}}{2} \tag{B66}$$

and

$$(T_A)_i = \frac{(T_A)_o + T_{SE}}{2} \tag{B67}$$

where:

T_S = well water temperature at location of interest as given by Collins.*

T_{SE} = shelter dry-bulb temperature at time for which boundary surface heat loss or gain is computed.

Substituting Equations (B66) and (B67) into Equation (B65) gives

$$\bar{T}_A = p_o(T_A)_o + \frac{p_S}{2}\left[T_S + T_{SE}\right] + \frac{p_I}{2}\left[(T_A)_o + T_{SE}\right] \tag{B68}$$

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* W. D. Collins, "Temperature of Water Available for Industrial Use in the United States", U.S. Geological Survey Water Supply Paper 520-F, 1925.

or

$$\bar{T}_A = (p_o + \frac{p_I}{2})\,(T_A)_o + \frac{(p_S + p_I)}{2}\, T_{SE} + \frac{1}{2}\, p_S T_S \tag{B69}$$

where:

$p_I = \sum_{i=1}^{q} p_i$, total percentage of shelter boundary surfaces exposed to interior spaces

The value of $\bar{T}_A$ of Equation (B69) is used as the value of T_A in Equation (B55). With these area weighted average property values and the relationship for $\bar{T}_A$, the value of the boundary surface heat loss or gain, Q_B, can be computed.

The analysis also considers the solar radiation that enters the shelter through windows and the solar radiation that is absorbed on the exterior surfaces of the shelter. The solar energy that comes through the windows is treated as a time varying thermal load in the Q_T term of Eq. (B2). The magnitude of this load is determined by

$$(Q_s)_{window} = (Q_s)_j\,(A_w)_j\,\gamma_j \tag{B70}$$

where:

$(Q_s)_{window}$ = energy transmitted into shelter at time of consideration

$(Q_s)_j$ = solar intensity on window j at time of consideration

$(A_w)_j$ = surface area of window j

γ_j = transmittance of window j for solar radiation

The solar energy that is absorbed by the walls is neglected as an assumption in the study of the shelters mentioned in the main body of this report. Therefore in Eq. (B54), ψ is taken to be equal to zero. Generally, this may be handled in the following way.

The solar energy that is absorbed by the wall is defined by the solar intensity Q_s times the absorptance of the exterior surfaces for solar radiation, ψ [see Eq. (B54)]. The value of Q_s that is used in Eq. (B54) is an area-weighted average value of the solar intensities that occur upon each of the boundary surfaces of the shelter exposed to sunlight. Consequently, this solar energy term is a function of time and is defined as

$$\overline{Q_s} = \frac{\sum_{j=1}^{n} (Q_s)_j A_j}{\sum_{j=1}^{n} A_j} \tag{B71}$$

where:

A_j = area of the bondary surface j, ft^2

n = number of bondary surfaces exposed to solar radiation at time for which $\bar{Q}_s$ is required

$(Q_s)_j$ = intensity of solar radiation incident upon the bondary surface, j, at time for which $\bar{Q}_s$ is required, $Btu/hr\text{-}ft^2$

The value of $(Q_s)_j$ is defined by

$$(Q_s)_j = (Q_{direct})_j + (Q_{diffuse})_j + (Q_{reflective})_j \tag{B72}$$

where:

$(Q_{direct})_j$ = energy received by surface j directly from sun, $Btu/hr/ft^2$

$(Q_{diffuse})_j$ = energy from atmospheric scattering which reaches surface j, from all directions in sky, $Btu/hr\text{-}ft^2$

$(Q_{reflective})_j$ = energy reflected from objects facing the surface j, that reach the surface j, $Btu/hr\text{-}ft^2$

B.2 COMPUTATIONAL CRITERIA

The time increment used in a computation cannot be arbitrarily chosen without introducing instability into the computations. Practice has shown that if the volume of the ventilating air introduced into the shelter during a time increment is less than a fixed percentage of the internal shelter volume, the calculations will be stable. That is,

$$60\,(\dot{F}_1)\,(\Delta\tau) \leq C\ V \tag{B73}$$

or

$$\Delta\tau \leq \frac{C\ V}{60(\dot{F}_1)} \tag{B74}$$

where:

- C = a constant coefficient ($\approx$ 0.1, by experience)
- $\Delta\tau$ = time increment, hr
- $\dot{F}_1$ = volumetric flow rate of entering ventilation air, ft^3/min
- V = shelter volume, ft^3

When a shelter's stability conditions are computed, the above stability criterion is the relationship that requires the smallest time increment, $\Delta\tau$, and not the relationships of Equations (B48), (B52), or (B56). Therefore, the size of the time increment is determined by Equation (B74).

Two other computational procedures that are followed in the mathematical model of the shelter are

1) the input data are linearly interpolated for time increments that are smaller than those for which the data are given, and
2) the relative humidity of the shelter is always kept less than or equal to unity. If the computed relative humidity is greater than unity, the latent heat input to the shelter is reduced until the relative humidity is equal to unity.

B3 - STEADY-STATE SHELTER ANALYSIS

In the steady-state analysis of the shelter environment, none of the parameters vary with time including the psychrometric condition of the shelter. This reduces the complexity of the computation program. The transient calculation procedure can be used to obtain steady-state environmental results if all of the parameters are made constant with time. The process is an iteration procedure which converges to the steady-state values. The steady-state calculation is otherwise identical to the transient shelter model.

Under steady-state conditions, the conservation of energy equation becomes

$$(H_1 - H_2) + Q_M + Q_T - Q_B = 0 \qquad \text{(B75)}$$

the conservation of the mass of water vapor is

$$(M_{V,1} - M_{V,2}) + M_{V,M} = 0 \qquad \text{(B76)}$$

and the conservation of dry air mass is

$$M_{a,1} - M_{a,2} = 0 \qquad \text{(B77)}$$

Introducing the quantities ΔQ, $M_{V,O}$ and $M_{a,O}$ as

$$\Delta Q = H_1 + Q_M + Q_T - Q_B \qquad \text{(B78)}$$

$$M_{V,O} = M_{V,1} + M_{V,M} \qquad \text{(B79)}$$

$$M_{a,O} = M_{a,1} \qquad \text{(B80)}$$

Then Equations (B75) through (B77) become

$$H_2 = \Delta Q \qquad \text{(B81)}$$

$$M_{V,2} = M_{V,O} \qquad \text{(B82)}$$

$$M_{a,2} = M_{a,O} \qquad \text{(B83)}$$

All of the other relationships remain the same as in the derivation of the transient analysis. The shelter's dry-bulb temperature is still defined by Equation (B20) and its relative humidity is still defined by Equation (B41) with the exception that the terms ΔQ, $M_{V,O}$, and $M_{a,O}$ must be defined as in Equations (B78) through (B80). One consequence of the steady-state derivation is that the shelter deminsions and volume do not enter into the calculations of the shelter's psychrometric condition.